Ageing and the Decay of Beauty

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Summary

This thesis marks the finalization of my PhD research. During the four years of my research, people frequently asked me about my work. I was surprised to notice that especially people from outside the work field of particle physics are very much interested in the work we do as particle physicists. I think their interest originates from questions that everyone asks themselves from time to time, such as 'what is matter made of?' and 'how did the universe begin and how will it end?'. These questions are essentially the motivation for our work. My hope is, that all the people that I have talked to in the last four years can enjoy reading at least parts of my thesis. Therefore, I will first start with a general introduction to particle physics, to explain the research I performed. After this, I will summarize the results of my analyses, guided by the title of my thesis. I will start with time-dependent CP violation using $B_s^0 \to J/\psi\,\phi$ (to be pronounced as *b sub s to jay psi fi*) events and conclude with the radiation hardness of the LHCb Outer Tracker.

Particle Physics and the LHC

The LHC is a particle accelerator that accelerates and collides protons in a circular underground tunnel. It stretches over 27 kilometers and is situated 100 meters below the surface. The protons collide millions of times per second in four distinct points along the LHC ring. Large particle detectors are installed surrounding the collision points to record the collisions or events. In this case, 'to record' means that the information about the passage of particles through the different subdetectors of the experiments is stored on computers. In the early days of particle physics, 'to record' would have meant to take a photograph of the event, as can be seen in Fig. S.1.

I performed my PhD research for the LHCb experiment, one of the four major experiments on the LHC accelerator ring. LHCb is a dedicated B physics experiment, as indicated by the additive 'b'. In B physics experiments, properties of B mesons are studied. To understand what these B mesons and their properties are, it is instructive to first have a look at the so-called Standard Model of elementary particles.

The Standard Model

The Standard Model (SM) describes our current knowledge of elementary particles and their interactions. It can be represented by a mathematical formula, but for the sake of simplicity it can be thought of as the set of all building blocks of nature, as shown in Fig. S.2.

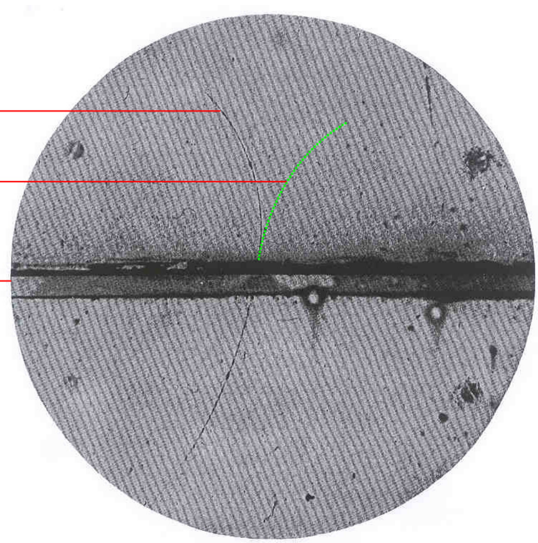

Figure S.1: *Photograph showing the discovery of an anti-electron, a so-called positron, recorded in 1932 by Carl D. Anderson. The identity of the positron is inferred from its direction of curvature, since it is opposite to the direction that is expected for an electron, indicated here by the dashed green line. The lead plate is used to slow down the incoming particle to deduce its direction of motion (upward or downward in the figure) from the difference in the radius of curvature on both sides of the plate.*

The SM is a theory that accurately predicts the many measurements that have been performed during the last decades. However, there are several known problems associated with it. One of these problems is well-known and was one of the reasons the LHC was built in the first place: to prove the existence of the Higgs boson.

Although I did not work on the Higgs search itself, the work that I performed on CP asymmetries is linked to Higgs particles. This is because the so-called Yukawa terms in the SM that express the couplings between the Higgs field and fermions to generate mass, are exactly the terms from which CP asymmetries arise, as explained in Chap. 1. I will now briefly elaborate on the Higgs search, since this puzzle might have been solved very recently.

The Higgs Boson

The Higgs particle was predicted in 1964 by, among others, Peter Higgs and is a necessary ingredient of the SM, since its presence generates mass for all other fundamental particles. It is being searched for in the ATLAS and CMS detectors, which are two other experiments on the LHC ring. July 4 2012 the ATLAS and CMS collaborations announced the discovery of a new boson whose properties are in agreement with the SM Higgs boson. This extraordinary finding was presented in a press conference held at CERN and was broadcasted worldwide

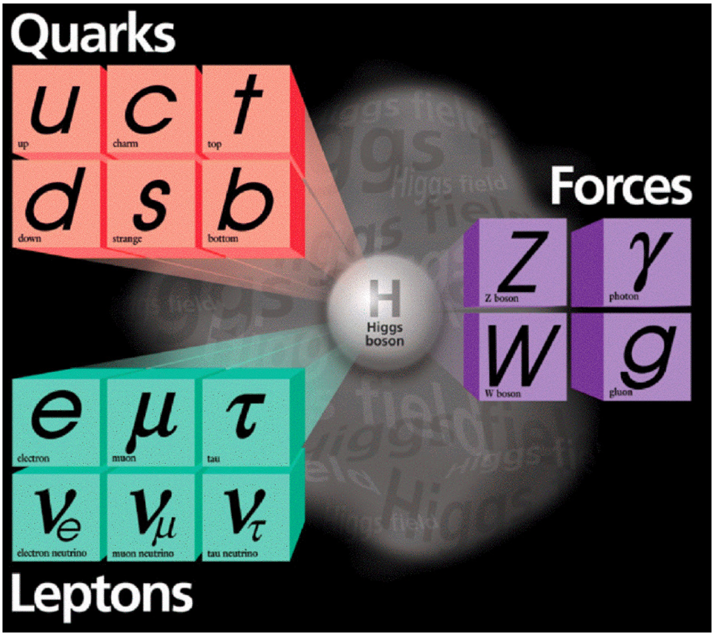

Figure S.2: *Schematic representation of the Standard Model, showing all the fundamental particles currently known. The Higgs boson (or, officially, a boson consistent with the SM Higgs boson) has been discovered on July 4, 2012.*

in the presence of Peter Higgs himself. The goal was not only observing the Higgs boson, but also to determine its mass. The ATLAS collaboration discovered a new boson with a mass of $126.0 \pm 0.6\,\text{GeV}/c^2$ [78], whereas the CMS collaboration independently observed a new boson with a mass of $125.3 \pm 0.6\,\text{GeV}/c^2$ [79]. In the coming years, at the LHC the properties of this new fundamental particle will be studied in order to test the SM. Whatever the results of those studies, the discovery of this new boson marks the end of a longstanding open question in the SM and in particle physics in general.

Fundamental Forces in the SM

The SM describes all elementary particles and their interactions. An interaction of a particle with one of the so-called force-carrier particles (Z, W, g and γ in Fig. S.2) is the manifestation of nature's fundamental forces. There are four fundamental forces in nature. Two of them can actually be observed in daily life. These are gravitation and the electromagnetic force (for example electricity). The two other fundamental forces of nature are the so-called weak force and the strong force. These two forces are less well-known, because their influence is only noticeable on very small (nuclear) scales. The weak force is involved in many radioactive decays, while the strong force acts as the proverbial glue that keeps quarks together to form protons or other bound quark states; so-called hadronic particles. The SM incorporates the strong, the weak and the electromagnetic forces. It does so through gluon particles (g), the

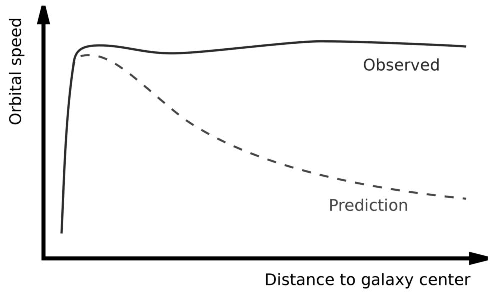

Figure S.3: *Stellar orbital speed as a function of distance to a galaxy center. Newtonian gravity predicts that the orbital speed decreases as a function of distance to the center, but observations prove otherwise. An explanation for this problem is dark matter, an unknown substance that does however feel gravity.*

Z and W particles and photons (γ particles) respectively. However, until now, physicists have been unable to incorporate gravity into the SM.

The Contents of our Universe

I have described two problems with the SM, namely the search for the Higgs boson and the incorporation of gravity. Another striking problem in particle physics deals with the content of our universe itself and arises from cosmological observations. When studying the orbital speed of stars at the outskirts of spiral galaxies, Newtonian gravitation predicts that the orbital speed decreases inversely with the square root of the radius of the orbit. However, observations [80] show that the orbital speed remains almost constant as a function of distance to the galaxy center, as indicated qualitatively in Fig. S.3. The best explanation so far is that there is some sort of invisible matter (here, 'matter' is a substance that is subject to gravity) in addition to visible matter, like that in stars. The ratio of known visible matter to this unknown so-called dark matter can be derived from the orbital-speed observations and amounts to a stunning one to five. Within the SM, there are no particles that can explain dark matter. Thus, the SM can account for only 20% of all the matter in the universe.

New Physics

To solve part of the problems associated with the SM mentioned above, theoretical physicists are trying to devise new mathematical models that incorporate and extend the SM. Such New Physics (NP) models make predictions for new types of particles, like dark matter candidates and new types of interactions. The experiments at the LHC are a unique environment for scientists to search for these new particles and interactions. These searches can be performed both in a direct way and in an indirect way. The former approach is used by the ATLAS and CMS detectors, by searching for the hypothetical particles in the decay products from the proton-proton collisions. In LHCb, however, the search for NP is performed indirectly, as

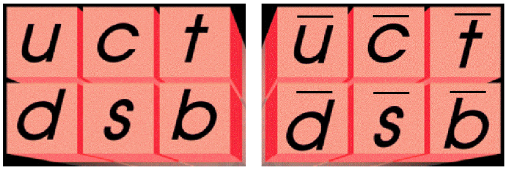

Figure S.4: *In 1928, Paul Dirac predicted that every fundamental particle has its own antiparticle associated with it. This is illustrated here for the six different types of quarks. For example, the up quark u, indicated on the left, has the anti-up quark as its associated antiparticle, indicated on the right by $\overline{u}$.*

LHCb measures parameters that are affected if new particles contribute to certain processes. When a significant deviation from the SM prediction is found, this could be an indication of New Physics. The measurement of such a parameter is the subject of my thesis and is denoted symbolically as ϕ_s. To explain what this parameter represents, another ingredient is needed: antimatter.

Antimatter

The schematic picture of the SM depicted in Fig. S.2 is actually incomplete. In 1928 the physicist Paul Dirac predicted the existence of so-called antimatter on mathematical grounds. This implied that every particle in the SM should have an antiparticle partner, as indicated for the quarks in Fig. S.4. Dirac was proven right in 1932, when the positron was discovered. A positron is the antiparticle of the well-known negatively charged electron, which means that it carries a positive charge. The photograph in Fig. S.1 shows one of the first positrons ever observed. Its identity was deduced from the direction of curvature in a magnetic field, since this was opposite to the direction that was expected for an electron, as indicated in the picture. When matter and antimatter particles meet, they 'destroy' or annihilate each other, producing photons. In the next paragraph I will explain B mesons and anti-B mesons, what CP violation means and how this relates to the parameter ϕ_s.

B mesons, CP Violation and ϕ_s

Mesons are quasi-stable particles that consist of two quarks. B mesons are mesons that contain one b or $\overline{b}$ (this denotes an anti-b) quark. These b quarks are sometimes called beauty quarks and, correspondingly, B mesons are occasionally referred to as beauty mesons. Here, since I have studied the decay of a beauty meson, we have arrived at the title of my thesis: The Decay of Beauty. The quark content of a B_s^0 meson is ($\overline{b}s$), while the decay products in $B_s^0 \to J/\psi\,\phi$ decays are the J/ψ meson ($c\overline{c}$) and the ϕ meson ($s\overline{s}$), as indicated in Fig. S.5.

The final ingredient that is needed to explain the parameter ϕ_s is a property of B mesons called mixing. Mixing means that B mesons can oscillate back and forth to their own antiparticle. This happens at an incredibly high frequency, roughly 18 trillion times per second. When two protons collide in LHCb, B_s^0 mesons and their antiparticles, $\overline{B}{}_s^0$ mesons, are produced in equal amounts. Due to mixing, the decay to the state $J/\psi\,\phi$ can take

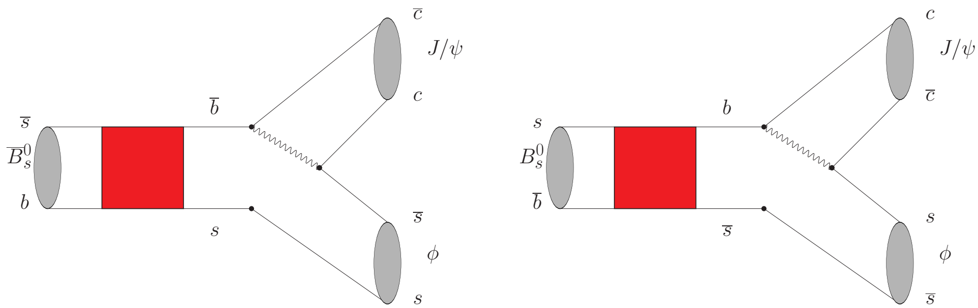

Figure S.5: *Left: schematic representation of a $\overline{B}_s^0$ meson oscillating to a B_s^0 meson (a process indicated by the red box) before decaying into the final state $J/\psi\,\phi$. Right: schematic representation of a B_s^0 meson oscillating to a $\overline{B}_s^0$ meson (again indicated by the red box) before decaying into the final state $J/\psi\,\phi$. Depending on the decay time of the B meson that was produced in the proton-proton collision, there is a possible difference in the decay rate of these two processes, which would be an indication of CP violation. The amount of CP violation is measured by ϕ_s and can be enhanced with respect to the SM prediction by NP processes in the red boxes.*

place at a moment when the parent particle was a B_s^0 particle, a $\overline{B}_s^0$ particle or even a quantum-mechanical superposition of the two.

Depending on the decay time of the B meson, there could be a difference in decay rate between decays where the originally produced particle was a B_s^0 meson and where the produced particle was a $\overline{B}_s^0$ meson. This effect is called time-dependent CP violation[1], represented graphically in Fig. S.5. The parameter ϕ_s is a measure of the amount of time-dependent CP violation in $B_s^0 \to J/\psi\,\phi$ decays. In the SM, ϕ_s is predicted to be very small, whereas NP models can enhance its value. Therefore, any significant deviation in ϕ_s from the SM prediction could be an indication of a New Physics discovery. In the next section, I will present the results of my ϕ_s measurement.

The Decay of Beauty: Time-Dependent CP Violation using $B_s^0 \to J/\psi\,\phi$ Decays

In the SM, ϕ_s is predicted to be $\phi_s = -0.036 \pm 0.002$ [17]. Any significant deviation from this prediction is an indication of New Physics. The value I measured is $\phi_s = 0.00 \pm 0.10\,(\text{stat.}) \pm 0.02\,(\text{syst.})$, which is in perfect agreement with the value as predicted by the SM. The result of my analysis can be presented and compared to earlier experiments by drawing contours in the $\phi_s - \Delta\Gamma_s$ plane as shown in Fig. S.6, where $\Delta\Gamma_s$ is the lifetime difference between two types of B_s^0 mesons. The smaller these contours, the more precise the measurement, therefore the measurement presented here is currently the most precise.

[1] The 'C' and 'P' in CP violation stand for charge and parity respectively. For more information, see Chap. 1.

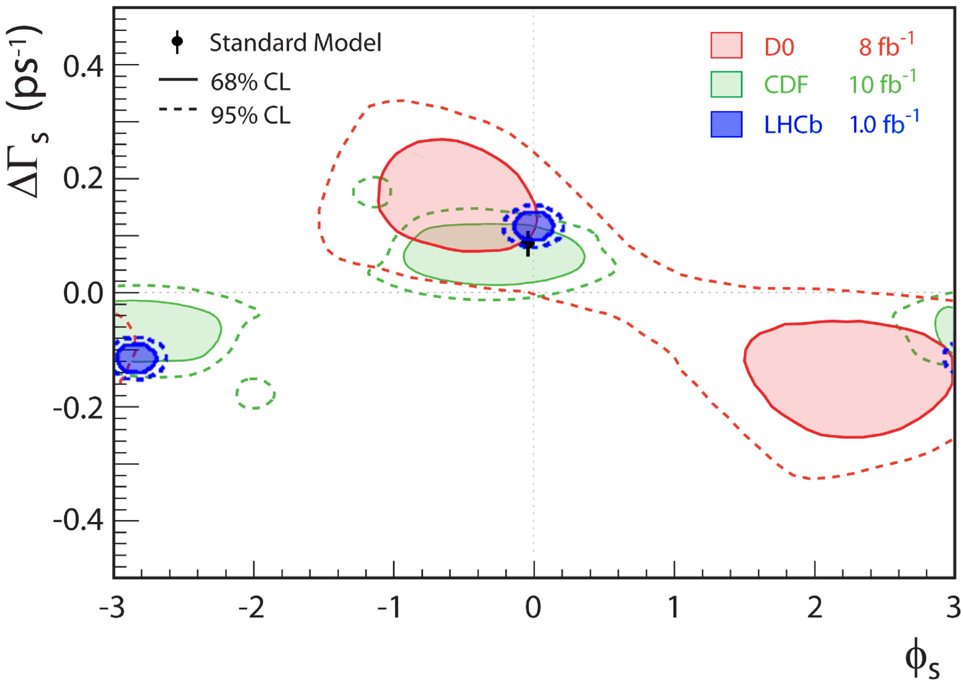

Figure S.6: *Two-dimensional confidence contours in the $\phi_s - \Delta\Gamma_s$ plane for the D0 collaboration [59] (red), the CDF collaboration [72] (green) and the values found in this analysis (blue). The black square indicates the SM point ($\phi_s = -0.036 \pm 0.002$, $\Delta\Gamma_s = 0.087 \pm 0.021\,\mathrm{ps}^{-1}$).*

Although the measured value for ϕ_s is in agreement with the SM, it is important to continue this analysis by adding more data and different decay channels that are sensitive to this parameter. This will reduce the uncertainty on the measurements and allow the observation of possible deviations from the SM. In the next section, I will summarize the second part of my thesis, which is related to the radiation hardness of the LHCb Outer Tracker.

Ageing: Radiation Hardness of the LHCb Outer Tracker

The Outer Tracker (OT) is one of the subdetectors of the LHCb experiment. It is used to reconstruct the trajectories of charged particles through the detector originating from proton-proton collisions. To detect a traversing particle, the OT uses straw tubes filled with an ionization gas that act as cathodes with a central anode wire. It consists of three detection stations and each station comprises 4 detection layers. The OT has a modular design, meaning that it consists of 432 modules of 128 straw tubes, leading to a total of roughly 55 000 straw tubes in the entire OT. The modules are constructed by glueing the straws to the module panels.

After construction and prior to installation of the modules in the LHCb experiment, laboratory tests [30] proved that outgassing of the glue that was used in the module construction reduced the performance of the detector modules. In the context of particle detector technology, effects that gradually reduce detector performance, such as outgassing, are collectively called ageing effects.

The modules that were installed in the LHCb cavern were subjected to several treatments to reduce or prevent ageing effects [41, 30, 42]. My thesis summarizes the results of tests that monitor the behavior of the OT modules after installation in the LHCb cavern. The effects of the beneficial treatments were tested by deliberately irradiating and scanning modules using a dedicated scanning setup which is installed in front of the modules. Before adding an oxygen component to the counting gas, several modules showed severe radiation damage after relatively small received dose, although large module-to-module variations were observed. After adding O_2 to the OT gas mixture, few to no radiation damage was observed.

To monitor the behavior of the OT modules after the startup of the LHC in 2009, two methods were devised. The first method uses the same scanning setup as described above to regularly perform reference scans of a subset of the modules. These scans are performed manually in the LHCb pit and can therefore only be performed during technical shutdowns of the LHC. The second method uses charged particle tracks produced by LHC collisions to study hit efficiency as a function of the amplifier threshold of the OT electronics. These so-called threshold scans are performed while the LHC is operational and producing collisions with tracks in the LHCb detector.

Both methods to monitor the performance of the OT modules were applied in my research. In this thesis, I conclude that neither method has shown any significant gain loss in the OT so far. Both types of tests are and will continue to be performed regularly to monitor the radiation hardness of the OT.